

INTERPRETATION OF THE 115 DAY PERIODIC MODULATION IN THE X-RAY FLUX OF NGC 5408 X-1

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ABSTRACT

We comment on the recent observation of a 115-day modulation in the X-ray flux of the ultraluminous X-ray source (ULX) NGC 5408 X-1, and in particular, the interpretation of this modulation as the orbital period. We suggest that this modulation may instead be due to a precessing jet, and is thus *superorbital* in nature. Comparing the properties of this ULX with those of the prototypical micro-quasar SS 433, we argue that NGC 5408 X-1 is very similar to SS 433: a hyper-accreting stellar-mass black hole in a shorter-period binary. If the analogy holds, the 115-day modulation is best explained by the still poorly-understood physics of inner-disc/jet precession and a longer observing baseline would be able to reveal an intrinsic phase jitter that is associated with such a precession.

Subject headings: accretion, accretion discs – black hole physics – galaxies: individual (NGC 5408) – X-rays: binaries – X-rays: individual (ULXs)

1. INTRODUCTION

The nature of ultra-luminous X-ray sources (ULXs) discovered by *Chandra* and *XMM-Newton* surveys of nearby galaxies remains highly controversial (e.g. Fabbiano & White 2006; Zampieri & Roberts 2009). ULXs appear as point-like, non-nuclear X-ray sources characterised by extremely high X-ray luminosities ($L_X \gtrsim 10^{39}$ erg s⁻¹) compared to *Galactic* X-ray binaries (XRBs) (Long et al. 1981; Fabbiano 1989; Makishima et al. 2000; Fabbiano, Zezas, & Murray 2001; Colbert et al. 2004).

Making seemingly reasonable assumptions that ULXs emit radiation isotropically and that they are Eddington limited, one might naturally conclude that ULXs harbour the long-sought intermediate-mass black holes (IMBHs) whose masses are $\sim 10^2$ – 10^4 M_\odot (Miller & Colbert 2004; Miller 2005; Fabbiano & White 2006). If IMBHs exist, they would be too light to plunge to the centres of their host galaxies via dynamical friction, but would be massive enough to power ULX luminosities.

NGC 5408 X-1 is one of the brightest ULXs, with a well-determined X-ray luminosity of $L_X \approx 2 \times 10^{40}$ erg s⁻¹ in the 0.3–10 keV band (Strohmayer 2009). Presently, this source is one of the best IMBH candidates, with mass estimates well in excess of 100 M_\odot , but possibly up to 9000 M_\odot (Kaaret et al. 2003; Strohmayer et al. 2007; Strohmayer 2009; Strohmayer & Mushotzky 2009). Such large range of uncertainty in the mass must surely be a cause for concern. This is particularly true given that a number of studies have suggested that ULXs may merely be stellar-mass black hole binaries (BHBs) that exhibit super-Eddington accretion which can be achieved via beaming of the emission, super-critical mass accretion, or a combination of both (Begelman, King, & Pringle 2006; King 2008a,b, 2009).

As a prime example of the difficulty in using the X-ray luminosity to pin down the black hole mass,

consider the case of SS 433, a remarkable Galactic X-ray source and the prototypical micro-quasar (see Margon 1984). SS 433 very likely contains a total mass ~ 40 M_\odot , with a ~ 4 M_\odot black hole as the compact accretor (Blundell, Bowler, & Schmidtobreick 2008; Kubota et al. 2010), and with the bulk of its energy output mechanically beamed (e.g. Begelman et al. 2006). Indeed, supporting evidence for the stellar-mass black hole scenario lies in the relativistic jets which precess with a 162-day period about the binary orbital axis. In addition, there are well-studied massive outflows due to hyper-Eddington mass transfer (Fabrika 2004; Begelman et al. 2006; Blundell et al. 2008). The jet itself has a kinetic luminosity $\gtrsim 10^{39}$ erg s⁻¹, which exceeds the observed L_X by a factor of $\sim 10^3$. However, its high orbital inclination obscures the intrinsic X-ray brightness from direct view. All of this together suggests that if viewed externally and at lower inclination, SS 433 would be bright enough to appear as a ULX (Fabrika & Mescheryakov 2001). Under these circumstances it would be miscategorised as an IMBH (Begelman et al. 2006).

Model-independent system mass estimates are possible in Galactic X-ray binaries based on their kinematics (Charles & Coe 2006). In the case of SS 433, the mass of the X-ray emitting accretor plus the accretion disc is $\approx 16 M_\odot$ (Blundell et al. 2008). However, such system mass estimates have not yet been possible for any extragalactic ULX.

Recently, a case for an IMBH in NGC 5408 X-1 has been made, citing its principal observed property of an extremely high L_X and the presence of a low-frequency quasi-periodic oscillation (QPO). The X-ray luminosity alone implies a black hole mass of ~ 100 M_\odot if we assume that the ULX is radiating at the Eddington limit. Adding weight to the interpretation that this source is an extreme form of high mass X-ray binary, there is a recent discovery of a 115-day modulation in the X-ray flux. Strohmayer (2009) interpreted this modulation as

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the binary orbital period for a system with a $\sim 1000 M_\odot$ black hole for the primary component and a 3–5 M_\odot giant or supergiant star for the secondary component.

In examining the properties of NGC 5408 X-1, we suggest here that it may be instructive to make further comparisons with SS 433. Both sources are known to be engulfed in photo-ionised, steep-spectrum radio nebulae of similar size (Margon 1984; Soria et al. 2006; Lang et al. 2007; Poutanen et al. 2007; Kaaret & Corbel 2009), strongly favouring the presence of optically-thin synchrotron emission powered by an accreting black hole over X-ray emission from a supernova remnant (SNR). And both may have formed from HMXBs undergoing mass transfer on a thermal time-scale (King et al. 2000). This raises the question of whether NGC 5408 X-1 may be more similar to SS 433 than previously realised. There now exists an extensive observational database for SS 433, particularly for its precessing jets (Eikenberry et al. 2001), and we investigate here whether its properties are sufficiently similar to those of NGC 5408 X-1 to consider them both part of the same population.

2. COMPARING NGC 5408 X-1 AND SS 433

2.1. Properties of NGC 5408 X-1

NGC 5408 is a dwarf irregular galaxy at a distance of 4.8 Mpc (Karachentsev et al. 2002). Kaaret et al. (2003) discovered radio emission at the position of the ULX NGC 5408 X-1, and they found that the X-ray, optical, and radio fluxes were consistent with beamed emission from a relativistic jet of an accreting stellar-mass black hole (although they could not rule out jet emission from an IMBH.) However, subsequent radio observations (Lang et al. 2007) showed that, in fact, the radio emission was too extended ($1''.5 - 2''.0$, or $R \approx 35 - 46$ pc) to be associated with relativistic jets and was more likely optically thin synchrotron emission from a surrounding nebula.

Because the ULX is located in a relatively unobscured and uncrowded region, its optical counterpart has been identified (Kaaret & Corbel 2009). It has been shown that NGC 5408 X-1 is confined within a photo-ionised nebula (of size $R \sim 30$ pc) displaying strong high-excitation emission lines of He II $\lambda 4686$ and [Ne V] $\lambda 3426$. The optical continuum emission of the counterpart was weak and there were no absorption features present that might be associated with the donor’s photosphere, thereby precluding a kinematic study (cf. Prestwich et al. 2007 in the case of IC 10 X-1; Kaaret & Corbel 2009).

A potentially crucial feature of this ULX is the presence of a low frequency ($\simeq 10$ mHz) quasi-periodic oscillation (QPO) in the soft X-ray band. (Strohmayer et al. 2007; Strohmayer 2009). The physical origin of such QPOs remains controversial (Poutanen et al. 2007). However, QPO phenomenology has been studied over the last decade, and it is commonly assumed that the black hole mass is inversely proportional to the QPO frequency at a given value of the power-law spectral index (Titarchuk, Lapidus, & Muslimov 1998; Titarchuk & Fiorito 2004; Shaposhnikov & Titarchuk 2009). Given this assumption, the observed QPO frequency suggests a black hole mass well in excess of $1000 M_\odot$, possibly as high as 9000

TABLE 1
COMPARING QPO FREQUENCY, P_{sup} , AND M_X IN BHBs.

| Source | P_{sup} [d] | f_{QPO} [Hz] | M_X [M_\odot] |
|--------------|-----------------------|---------------------------|---------------------|
| NGC 5408 X-1 | 115.5 ± 4^a | 0.010^a | — |
| SS 433 | 162.375 ± 0.011^b | 0.100^c | 4.3 ± 0.6^d |
| GRS 1915+105 | 590 ± 40^e | $0.001\text{--}67^f$ | 14 ± 4^g |
| GRO J1655-40 | $\simeq 3^i$ | $0.1\text{--}450^{j,k,m}$ | 6.3 ± 0.5^n |
| Cygnus X-1 | $\simeq 300^p$ | $0.040\text{--}0.070^q$ | 21 ± 8^p |

^aStrohmayer (2009). ^bEikenberry et al. (2001). ^cKotani et al. (2006). ^dKubota et al. (2010). ^eRau, Greiner, & McCollough (2003). ^fMorgan, Remillard, & Greiner (1997). ^gGreiner et al. (2001). ^hHjellming & Rupen (1995). ^jRemillard et al. (1999). ^kStrohmayer (2001). ^mRemillard et al. (2002). ⁿGreene et al. (2001). ^pRico (2008). ^qVikhlinin et al. (1994).

M_\odot (Strohmayer & Mushotzky 2009). If these properties were confirmed, then NGC 5408 X-1 would indeed be a remarkable and extremely important object for black hole population studies.

2.2. Properties of SS 433

A twenty-year baseline of many optical photometric and spectroscopic campaigns has revealed multiple periodicities in SS 433: a well-established orbital period of $P_{orb} = 13.07$ d (Crampton, Cowley, & Hutchings 1980), a precessional period $P_{prec} = 162.375$ d (Eikenberry et al. 2001), and a nutation period $P_{nu} = 6.3$ d (Mazeh et al. 1980; Katz et al. 1982) due to a periodic torque produced by the secondary component which does not affect the mean precession rate but does produce an instantaneous oscillation in the precession with a period of about one-half the orbital period (Katz et al. 1982; Bate et al. 2000).

SS 433 has an observed X-ray luminosity of $L \sim 10^{36}$ erg s^{−1}, but as an eclipsing binary, it has a high inclination and fits the description of a classic *accretion disc corona* (ADC) source (Watson et al. 1986; Frank, King, & Lasota 1987); the obscuration by the disc implies that the intrinsic L_X is a factor 10^{2-3} higher. The observed kinetic luminosity in the jets is in the range $L_k \sim 10^{39-41}$ erg s^{−1} (Margon 1984; Fabrika 2004). As pointed out in King (2008b), this kinetic luminosity is already larger (possibly very much so) than the Eddington luminosity for a $\sim 10 M_\odot$ black hole. The mass ejection rate from the jets is $\dot{M}_{jets} \gtrsim 5 \times 10^{-7} M_\odot \text{ yr}^{-1}$ (Begelman et al. 2006).

SS 433 is located at the centre of the supernova remnant W50 whose size is $\approx 1.5^\circ$ across its largest dimension, corresponding to ≈ 64 pc at its distance of 5.5 kpc (Margon 1984). It is worth noting that this is comparable in extent to that of the NGC 5408 X-1 optical nebula. W50 has long been known to exhibit “ears” that align with the SS 433 jets, perhaps caused by the strong outflowing wind velocity of ≈ 1500 km s^{−1} (Fabrika 2004). These winds may be driven by hyper-Eddington accretion onto the black hole at $\approx 5000 \dot{M}_{Edd}$ (Begelman et al. 2006; see also Fig. 9 of Shakura & Sunyaev 1973). Such a hyper-accreting object will generate a mechanically beamed accretion luminosity (Begelman et al. 2006; King 2008a). Consequently, most of the light is geometrically collimated into a cone along the outflow axis with a solid angle Ω that cannot be estimated *a priori*, since its inverse determines the apparent luminosity. For con-

sistency with the number of progenitor high mass X-ray binaries in the Milky Way, it is assumed that $\Omega/4\pi \gtrsim 0.1$ for SS 433 (Begelman et al. 2006; Fabrika & Abolmasov 2007; Poutanen et al. 2007; King 2008a,b, 2009).

3. THE NATURE OF THE 115-DAY PERIODIC MODULATION IN NGC 5408 X-1

A 115^d5 modulation was detected in the X-ray flux of NGC 5408 X-1 with the *Swift*/X-ray Telescope and was interpreted as being orbital in origin (Strohmayer 2009). Since the stability of this modulation has not yet been established, this conclusion was largely based on the assertion that 115 days is shorter than all other known superorbital periods for stellar mass BHBs in the Galaxy. However, it is not substantially less than the well-established superorbital precession period for SS 433.

In fact, the question of whether there is significant overlap in the orbital timescales of black holes and neutron stars remains unanswered to date. Superorbital periods in neutron stars are known to range from tens to hundreds of days (Wen et al. 2006; Charles et al. 2008)—in some cases even longer than the 115 days in NGC 5408 X-1 (Charles et al. 2008; Kotze & Charles 2010). Taking into account that there are considerably more known neutron star binaries than BHBs, that there are a comparatively small number of known, persistently bright black hole candidates, and that there are *several* mechanisms to explain these periodicities (i.e. the Kozai mechanism, radiation-driven disc warping, etc.; Kozai 1962; Maloney, Begelman, & Nowak 1996, 1998), the need for a comprehensive statistical analysis of the orbital timescales in neutron stars and black holes is apparent.

So far, the modulation period in NGC 5408 X-1 has only been determined to ± 4 days as a result of the small number of cycles sampled. We note that if the 115 d modulation is orbital, then longer observing baselines will define this more and more precisely, whereas a superorbital modulation (such as for SS 433) will suffer an intrinsic phase jitter. At this time, the observations cannot distinguish between the two interpretations and we propose here that the modulation is instead superorbital in origin and hence similar to SS 433.

4. DISCUSSION

4.1. Mass estimates from QPOs

For Galactic BHBs with high Eddington ratios (L/L_{Edd}), there exist kinematic data that constrain their masses to be $\sim 10\text{--}15 M_{\odot}$ (e.g. GRS 1915+105, Greiner et al. 2001). However, for ULXs there is no such dynamical information due to their extreme optical faintness and lack of direct detection of the donor. Therefore, we must use indirect methods.

Under the assumption that they are signatures of Keplerian orbits of the material in the inner accretion flow, low-frequency QPOs have been used to infer the masses of the primary components of BHBs. This line of enquiry seems promising in light of more recent work (Shaposhnikov & Titarchuk 2009), although the techniques involved have thus far only been applied to a small number of stellar-mass black holes ($M_{\text{BH}} \sim 5\text{--}15 M_{\odot}$), so the range of masses sampled is low.

NGC 5408 X-1 is a ULX whose observed properties suggest two different masses for its compact accretor. The L_X alone implies a $\sim 100 M_{\odot}$ black hole if we assume a high Eddington ratio. Yet, this ULX exhibits a low-frequency QPO in its soft flux, suggesting the presence of an IMBH of mass $2000\text{--}5000 M_{\odot}$ (Strohmayer & Mushotzky 2009). However, similar low-frequency oscillations have been observed in Galactic binaries that are well-established *stellar-mass* binary systems (see Table 1). For example, GRS 1915+105 exhibits low-frequency QPOs $\sim 0.001\text{--}10$ Hz (Morgan, Remillard, & Greiner 1997) and Cygnus X-1 has low-frequency QPOs $\sim 0.04\text{--}0.07$ Hz (Vikhlinin et al. 1994). Furthermore, the sample of stellar mass BHBs used to determine the scaling relationship (which is based on the range of the best-fitting power-law slopes in their reference sample of sources) for NGC 5408 X-1 in Strohmayer & Mushotzky (2009) uses systems with known stellar-black-hole masses whose observed Eddington fraction is much higher than would be the case for NGC 5408 X-1 if its black hole has a mass of $5000 M_{\odot}$ (as predicted in Strohmayer & Mushotzky 2009) and therefore $L_{\text{Edd}} \gtrsim 10^{42} \text{ erg s}^{-1}$. The observed $L_X \approx 2 \times 10^{40} \text{ erg s}^{-1}$ is only $\sim 2\%$ L_{Edd} and this may not be reasonable given the environment of this ULX and the apparently steady flux level. Therefore, one should exercise caution when using the presence of low-frequency QPOs to infer black-hole masses.

4.2. Mass Transfer from the Donor

Two distinct effects of super-Eddington mass transfer can cause the X-ray luminosity to exceed the Eddington limit. First, the disc accretion luminosity has an additional, logarithmic component due to the inner transition region:

$$L_{\text{acc}} \simeq L_{\text{Edd}} \left[1 + \ln \left(\frac{\dot{M}}{\dot{M}_{\text{Edd}}} \right) \right] \quad (1)$$

which could enhance the luminosity by as much as 5–10 times L_{Edd} (Poutanen et al. 2007). Secondly, the luminosity is modified by mechanical (i.e. geometrical, non-relativistic) beaming, resulting in collimation by a factor b (typically $\gtrsim 0.1$):

$$L \simeq \frac{L_{\text{Edd}}}{b} \left[1 + \ln \left(\frac{\dot{M}}{\dot{M}_{\text{Edd}}} \right) \right] \quad (2)$$

(King 2002; Rappaport, Podsiadlowski, & Pfahl 2005; Poutanen et al. 2007; King 2008a,b). Hence it should not be considered surprising that X-ray emitting binaries can exceed L_{Edd} by as much as an order of magnitude in certain circumstances.

A key point to consider is that for SS 433, a system with mass ratio $M_2/M_X > 1$, the inferred mass transfer rate ($\sim 10^{-4} M_{\odot} \text{ yr}^{-1}$) requires that it is in a very short-lived phase (Begelman et al. 2006). The clear implications are that either such systems are very rare, or their mass transfer rates are highly variable and/or the systems are very young, being located in star-forming regions.

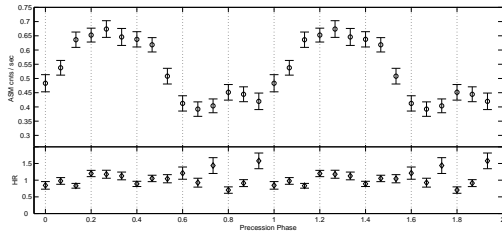


FIG. 1.— *Top panel:* RXTE/ASM count rate (vertical axis, in cts s^{-1}) for SS 433, plotted against precession phase (horizontal axis). *Bottom panel:* ASM hardness ratio, defined as C-band / (A-band + B-band), versus precession phase. The precession period is 162 days (Eikenberry et al. 2001).

4.3. Is the 115-day modulation due to disk/jet precession?

The observed modulation in the X-ray flux of NGC 5408 X-1 is $\approx 13 - 24\%$, depending on energy. Roughly the same levels of modulation were observed in SS 433 (Gies et. al 2002). These energy-dependent modulations in both SS 433 and NGC 5408 X-1 could be a common feature of such systems, and the spectral effects are perhaps simply related to the orientation of the precessing discs relative to our line of sight.

Figure 1 illustrates the relationship between the modulation and hardness ratio for SS 433. The relative flatness of the hardness ratio for SS 433 compared with that of NGC 5408 X-1 (cf. Figs. 3 and 4 of Strohmayer 2009) may be accounted for by the difference in viewing angle; that is, SS 433 is an ADC source whose spectrum is modified by its obscuring corona but the same effect is less pronounced in NGC 5408 X-1 because of its lower inclination. Notably, the effect of absorption and emission of X-rays by a partially ionised wind from a companion star was suggested as a link between the energy-dependent amplitudes of the 115-day modulation and the orbital period of the system (Strohmayer 2009); however, the same effect should be present in the case of SS 433 but is not. Also, the effect of beaming could concentrate the soft emission, which would explain the softening of the emission in NGC 5408 X-1 that occurs when the source brightens as a result of its assumed precession (Begelman et al. 2006). We suggest, therefore, that the 115-day periodicity found by Strohmayer (2009) for NGC

5408 X-1 is more likely superorbital in nature and similar to SS 433. This has implications for the determination of the black hole mass in ULXs, significantly reducing the mass needed to produce the observed properties.

5. CONCLUSIONS

If the nature of the ultra-luminous X-ray source (ULX) NGC 5408 X-1 is similar to that of the Galactic microquasar SS 433, then this ULX may be best described as an extragalactic high mass X-ray binary undergoing mass transfer at or near the Eddington rate, but at a lower inclination than would be typically seen in an accretion disc corona source (Begelman et al. 2006; Fabrika & Abolmasov 2007; King 2009). This would mean that in the case of NGC 5408 X-1, we are viewing the hot inner accretion flow, substantially boosting the apparent brightness of this source. The 115 day periodicity could be due to precession of the inner-disc/jet of NGC 5408 X-1, similar to SS 433, and not necessarily the orbital period as assumed in Strohmayer (2009).

With *Chandra* or *XMM-Newton*, the best currently-available X-ray imaging telescopes, the count rate is typically too low to resolve the nature of the 115-day modulation in NGC 5408 X-1. Settling this will be possible with a next-generation X-ray facility that has a greater collecting area. Indeed, it is certainly possible that the entire class of ULXs are merely high mass X-ray binaries that are undergoing super-critical mass accretion onto a stellar-mass black hole, substantial beaming, or a combination of both. If we can confirm that NGC 5408 X-1 does contain a stellar-mass black hole, the link between ULXs and intermediate-mass black holes will have been severely challenged.

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